Laser communication, clock synchronization, and ranging in interferometric space missions.

Rodrigo Delgadillo, Wan Wu, Ira Thorpe, Shawn Mitryk, Volker Quetschke, Guido Mueller
University of Florida
PO Box 118440
Gainesville, FL 32611 USA

Abstract—**Several NASA missions, like LISA, Lator, Maxim, any Grace follow-on mission, and others, utilize laser interferometer to measure changes in distances between the various spacecraft. These laser interferometers are usually interferometers with substantial arm length differences and require sophisticated phase measurement capabilities to reach their limit which is often set by shot noise or laser frequency noise. In many cases the measurement system is also required to synchronize and stabilize the clocks on each S/C and perform ranging measurements to retrieve the absolute distance between the S/C. In addition to this, the S/C also need to communicate directly with each other to exchange status information or exchange other data. Each of these tasks can usually be performed by customized individual systems, but it is much more desirable to combine all these tasks with the main interferometry to reduce mass and energy consumption. Such a multi-task system has to show that its various additional functions do not interfere with each other and especially not with the main interferometry. Our group has developed a scheme to exchange clock synchronization, clock stabilization, ranging, and data information using the main interferometer link and is currently in the process of studying implementation strategies to reduce the interference with the main interferometer signal. This work is supported by NASA grant APRA04-0048-0006.**

I. Introduction

Formation flying and space interferometry are key technologies to pursue goals like the exploration of the Universe and the search for evidence of life, which is one of the main strategic goals of NASA's Beyond Einstein [1] and NASA's Origin [2] programs. Missions to trace out the Earth's gravitational field (GRACE follow-on: EX-5) [3], gravitational wave detector missions (LISA [4], BBO [1]), and large baseline telescope missions (Maxim [5]) will only be the first of a series of projects which depend on these technologies.

The distances between S/C in the various missions can range from about 10 km (Maxim) and 100 km (EX-5) up to 5 Gm (LISA). The necessary resolution in the laser interferometry ranges from 10 nm (EX-5) to 10 pm (LISA). It is virtually impossible to design and test a system that would fit all possible applications and meet the requirements of all missions. However, they all use laser interferometry to sense changes in the separation between the spacecraft. Also, all the missions require some knowledge about the absolute distance between the spacecraft (ranging), need to exchange information about the status of each S/C, and have to synchronize their clocks.

In principle, all these functions could be entertained by the laser link. One pair of sidebands for each function can be modulated onto the carrier and detected at the other S/C. Subsequently, several RF-signals would be generated at the photo receiver. Each signal has to be identified, separated from the others, and postprocessed to extract the embedded information. This has to be done for each sideband without interfering with the main interferometry signal or with the other sidebands. Several electro-optic modulators and high voltage power supplies would be necessary to apply all modulations with the appropriate amplitude. The result is a rather complex system with many hardware components and a high probability of failure.

Our group studies a compact laser communication and ranging system for interferometric space missions which uses a single modulation tone modulated on the main laser field. This system will be capable of transfering data between spacecraft, synchronizing the clocks on both spacecrafts, and measuring the macroscopic distance (ranging) and the microscopic changes in the distance (interferometry) between the spacecraft simultaneously. The basic system should be applicable to missions with moderate requirements like Maxim, or EX-5, where the distances between spacecraft are below 100 km and the required interferometric sensitivity is above 1 nm over 1000 s. However, the goal is to keep the system flexible enough to accomodate changes and/or specific requirements for more demanding missions like LISA or BBO.

II. Technilogical Approach

Each S/C carries one laser and one clock. The phase of each laser field will be modulated with a single modulation frequency, $\Omega_i, i = 1, 2$, which generates a pair of sidebands around each carrier field. The modulation signal is derived from the on-board clock. The phase of the modulation signal contains information about the time of the local clock while the phase noise is proportional to the timing noise or timing jitter of the clock. Data streams are encoded in the amplitude of the modulation signal.

The beat signals between the two carrier fields are the main interferometer signals. They are used to measure the changes in the distance between the S/C with sub-nm accuracy. The sensitivity of this signal often depends on the laser frequency noise of the lasers. In many cases one laser will act as a master laser to which all other lasers are phaselocked. The frequency of the master laser itself will often be stabilized to

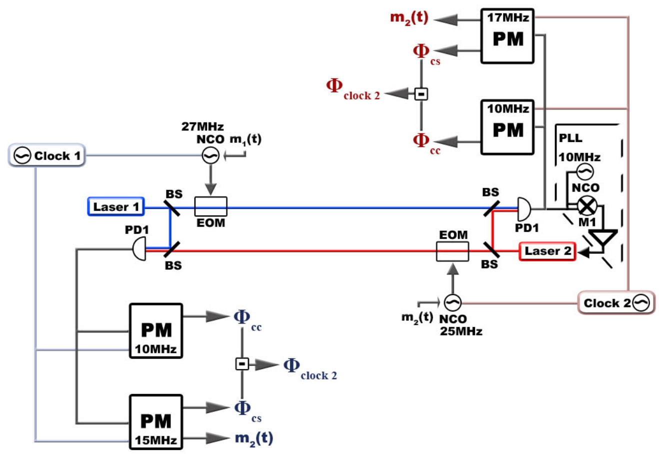

Figure 1. Experimental Setup. The optics table has four beam splitters arranged closely together. Each arm has an electro-optic modulator (EOM), a photo detector (PD), a reference clock, and two phasemeters (PD) that measures the amplitude and phase of the beat signals. Then, the difference between carrier/carrier and carrier/sideband phase is taken to produce the clock phase. An optional phase-lock loop (PLL) is shown in dashed lines.

an optical frequency reference like an optical cavity, an atomic or molecular transition, or to the arms of the interferometer.

The beat signal between the local carrier and one of the sidebands from the other spacecraft is also demodulated with an oscillator which is locked to the local clock. The difference between the phase of this demodulated signal and the phase of the main interferometer signal depends on the macroscopic distance (ranging) between the spacecraft and the phase of the sideband which in turn depends on the clock on the far spacecraft which generated the sideband. A similar signal is also generated on the far spacecraft. After exchanging these phase informations using the data link (or ground links), linear combinations can be formed which measure the light travel time between the spacecraft (ranging) and differences in the clocks (clock synchronization) on the two spacecraft.

The amplitude of the demodulated carrier/sideband beat contains the data stream. This amplitude can be recovered when we demodulate both quadratures of the beat signal and reconstruct the amplitude. A second possibility is to use a tracking filter which reduces one quadrature to zero and monitor only the other quadrature. This technique is commonly known as amplitude shift keying. The additional beat signal between the local carrier and the second sideband from the far spacecraft contains redundant information and might be used to improve the signal to noise ratio or verify that the system works as expected.

An experimental realization of our proposed laser communication and ranging system is shown in Fig.1. The frequency of one of the laser fields, say laser 1, is pre-stabilized to either an optical cavity or a molecular resonance. Typical values for the achievable relative frequency stability are in the range of 10^{-13} to 10^{-14} over 1000 s [6,7]. Parts of the field are then separated from the main beam and are superimposed with the field received from the far S/C. The beat signals, taken with a photo detector (PD), contain several frequency components. On S/C 2, the laser would be phase locked to the incoming carrier field at a difference frequency $\Delta\omega$. This S/C acts like a transponder for the laser beam from S/C 1. The phase evolution in the equivalent demodulated signal (IFO) on S/C 1 is proportional to the changes in the distance between the S/C:

$$\delta\phi = 2\pi\frac{\delta l(t)}{\lambda}$$

The relative accuracy of this one-arm measurement will often be limited by the frequency stability of the first laser:

$$\frac{\delta l}{L} = \frac{\delta\nu}{\nu} \approx 10^{-13} - 10^{-14}$$

It is also possible to use the IFO signal to stabilize the laser frequency with respect to the distance between the S/C. This technique is called arm locking [8]. It does not improve the sensitivity directly but it can have advantages in some situations as it keeps the IFO signal at a nominal working point. Note that in many of the above mentioned missions only the difference between distances is critical while the requirements on the absolute distance are relaxed. This results in a much improved sensitivity for differential length changes as the laser frequency noise is common in all measurements and cancels in the difference [9].

On both S/C the beat tone between the carrier and the far sideband is then demodulated with the known frequency $\Delta\omega \pm \Omega_{1/2}$, where $\Omega_{1/2}$ is the modulation frequency at the EOM of the far S/C. The difference between the phase of this signal and the phase of the main interferometer signal depends on the macroscopic light travel time τ (ranging information) and the difference in the clocks Δt which generate the modulation and the demodulation frequencies:

$$\Psi_1 = \Omega_1\left(\tau + \frac{\Delta t}{2}\right) \qquad \Psi_2 = \Omega_2\left(\tau - \frac{\Delta t}{2}\right)$$

The weighted sums and differences:

$$\Delta t = \frac{\Omega_1\Psi_1 - \Omega_2\Psi_2}{\Omega_1\Omega_2} \qquad \tau = \frac{\Omega_1\Psi_1 + \Omega_2\Psi_2}{2\Omega_1\Omega_2}$$

give the ranging information and any clock offsets. Variations in these phase differences are proportional to the relative noise between the two clocks and can be used to subtract clock noise from the demodulated interferometer signal.

In our experimental setup shown in Figure 1 we use two diode pumped Nd:YAG lasers. The four beam splitters (BS) and the EOM will be mounted as close as possible to each other on a Super Invar breadboard to reduce the low frequency distortions. The light from Laser 1 is split at the upper left BS. The reflected field is superimposed with the incoming field from Laser 2. The transmitted field travels through one of the EOMs where it is modulated by a 27 MHz signal. The RF signal is generated by a numerically controlled oscillator (NCO) and has a variable amplitude $m_1(t)$. This light is superimposed at the upper right BS with the light from Laser 2. The field from laser 2 is split at the lower right BS. The reflected part is superimposed with the phase modulated field

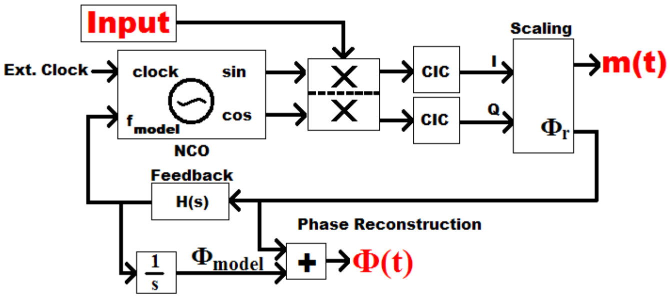

Figure 2. Phasemeter. The model frequency's sine and cosine components mix seperately with the input signal to produce the I-Q components. These can be used to produce the amplitude, $m(t)$, and residual phase, $\phi_r(t)$. The cascaded integrated comb (CIC) filter output is used to feedback to the model frequency, f_{model}. The input signal phase, $\phi(t)$, is reconstructed using $\phi_r(t)$ and the model phase, $\phi_{model}(t)$.

from laser 1 at the upper right BS. The transmitted field can be phase modulated by the second EOM before it is superimposed with the unmodulated field from laser 1 at the lower left BS. The signal at PD2 contains a 10MHz carrier/carrier beat signal and two carrier/sideband beat signals of 17 MHz and 37 MHz. Both carrier/sidebands carry the same information so that one carrier/sideband is redundant.

The path from the Laser 2 side to Laser 1 side is similar. They are parallel systems which allow for communication both ways from one S/C to the other S/C.

Each beat signal is connected to a fast analog to digital converter (ADC) which samples the beat signals in our case with a 100 Ms/s data rate. These data streams are fed into a field programmable gate array (FPGA) which runs two phasemeters (PM). Each PM includes a numerical controlled oscillator which generates a sine and cosine wave (or inphase I and quadrature Q component) at a model frequency. These waves are multiplied in real time with the digitized data stream. The demodulated Q component is downsampled and filtered by a cascaded integrated comb (CIC) filter and then used to phase lock the NCO to the incoming signal by updating its model frequency. The actuation signal to the NCO as well as the residual phase difference $\delta\phi \approx Q/I$ is used to calculate the phases of the carrier/carrier and carrier/sideband beats with respect to the S/C clock which drives the NCO. The amplitude of the signal is proportional to $\sqrt{I^2+Q^2} \approx I$ as Q is suppressed by the phase lock loop. These phasemeters were originally developed for the LISA mission and are discussed in more detail in [10]. They can lock to several frequencies simultaneously as long as the frequencies are separated by more than about 1 MHz.

Some missions might also use the carrier/carrier beat signal to phase lock the two lasers with an offset frequency which is also derived from the on-board clock. This could make the phase lock loop in the PM obsolete. Note that this can not always be done as the spacecraft might encounter a relative motion with respect to each other leading to Doppler shifts [10].

The carrier/carrier phases contain now information about

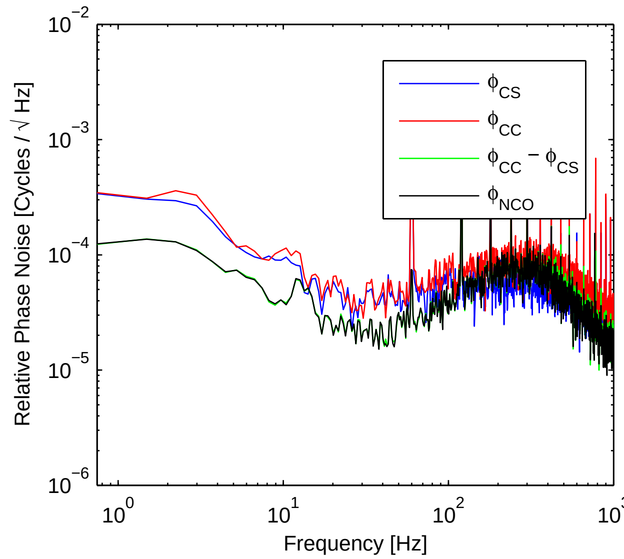

Figure 3. Relative phase noise of the beat signals, difference between the beat signals, and NCO that drives the EOM.

the minute changes in the distance between the two spacecraft while the sum of the carrier/sideband phases is proportional to the signal travel time and the difference to clock offsets. All signals are compromised by laser frequency noise and clock noise. However, as the sideband itself is essentially generated by the clock, the dependency of the carrier/sideband phases from clock noise is different than the dependency of the carrier/carrier phases from clock noise. This difference can be used to extract the clock noise from all signals.

In a first experiment, we used only one of the interferometer arms to verify the accuracy of the detection scheme. We modulated the phase of Laser 1 with 27 MHz using the EOM. The 27 MHz was derived from a non-stabilized oscillator. This modulated field was then superimposed with Laser 2 and then detected with a fast photodetector. The carrier/carrier beat signal was demodulated with a 10 MHz signal from an ultra-stable clock and used to offset-phaselock Laser 2 on Laser 1. The beat signal was then digitized and sent into two phasemeters which locked at the 10 MHz carrier/carrier beat frequency and the 17 MHz carrier/sideband beat frequency. The linear spectral densities of the measured phases are shown in 3. Both signals ϕ_{CC}, ϕ_{CS} are highly correlated as they both show mainly the residual phase noise of the imperfect phaselock loop. The linear spectral density of the phase noise of the difference $\phi_{CC} - \phi_{CS}$ and the phase noise of the 27 MHz clock frequency are also shown. The difference is highly correlated with the clock noise and this signal could be used to measure the clocks against each other.

In the next weeks we will improve the phase noise of our 27 MHz signal and the detection sensitivity. Then we will add the second arm and will start measurements where we exchange clock noise on the laser beat signals and then add data streams either by modulating the phase or the amplitude of the modulation sidebands.

This work is supported by NASA grant APRA04-0048-0006. Parts of the measurements were done in collaboration with the UF-LIGO group which is supported by NSF grant PHY-0354999 and PHY-0555453

REFERENCES

[1] NASA's Beyond Einstein program is described on http://universe.gsfc.nasa.gov.
[2] NASA's Origin program is described on http://origins.jpl.nasa.gov
[3] GRACE is described in detail at http://www.csr.utexas.edu/grace/
[4] LISA is descibed in detail on http://www.lisa.jpl.gov.
[5] Maxim: The Micro-Arcsec X-ray Imaging Mission will probe the extreme environment in the vicinity of a black hole. See http://maxim.gsfc.nasa.gov, also known as the Black Hole Imager in the Beyond Einstein program
[6] Miao Zhu, John L. Hall, Short and Long Term Stability of Optical Oscillators, IEEE Frequency Control Symposium, pp. (1992). See also: B.C. Young, F.C Cruz, W.M. Itano, J.C. Bergquist, Visible Lasers with Subhertz Linewidths, Phys. Rev. Lett. 82(19) (1999) and Holger Muller, Sven Herrmann, Claus Braxmaier, Stephan Schiller, Achim Peters, Modern Michelson-Morley Experiment using Cryogenic Optical Resonators, Phys. Rev. Lett. 91(2) (2003)
[7] R. J. Cruz, Development of the UF LISA Benchtop Simulator for Time Delay Interferometry, Ph.D. dissertation, The University of Florida, May 2006.
[8] B.S. Sheard, M.B. Gray, D.E. McClelland, D.A. Shaddock, Frequency Stabilization by Locking to a LISA arm, Phys. Lett. A. 320 9-21 (2003)
[9] M. Tinto, F.B. Estabrook, J.W. Armstrong, Time-Delay Interferometry with Moving spacecraft arrays, Phys. Rev. D. 69, 082001 (2004)
[10] James I. Thorpe, Rachel J. Cruz, Shawn Mitryk, G.T.S. Reddy, and Guido Mueller, Benchtop Models of LISA Interferometry at the University of Florida, In these NSTC2007-Proceedings.